Solar Energetic Particles
– acceleration and observations —

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Summary. *The study of Solar Energetic Particles (SEPs) is important to understand particle acceleration, transport and interactions taking place in the universe. The importance to modern human life of space weather is also increasing. In this lecture, I introduce a subset of the variety of SEP observations together with observation techniques and future plans. The aim of this SEP study is to compile these observations into acceleration mechanisms through their transport and interaction processes. Because the various observational properties are determined through different processes, variety of observations are necessary in order to fully understand the phenomena taking place. I also overview the role of the SEP studies in general astrophysics.

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1 What are Solar Energetic Particles

We know that the sun is shining stably in visible light, but it is dynamic in shorter wavelengths, i.e. higher energies. Dynamic activity sometimes produces violent eruptions that release huge amounts of energy in short time intervals. In eruptions such as solar flares and coronal mass ejections, particle acceleration to relativistic energies occurs. These particles and their high energy secondaries are called Solar Energetic Particles, SEPs in short. Particle acceleration is a common process taking place over the universe. For example, supernova remnants, active galactic nuclei, gamma-ray bursts, etc... [**?**]. However, details of the mechanism of particle acceleration is not yet fully understood, especially about ion acceleration though ions are major element of cosmic-rays. By the way, because the sun is one of the robust astronomical ion accelerators, it is thought to be a natural laboratory to study particle acceleration processes. Although the maximum energy achieved by acceleration near the sun is far below the cosmic-ray energy, we know when and where the particles are accelerated. Together with simultaneous observations at wide wavelengths, of various particles with high resolution, the study of SEPs has great advantages to investigate particle acceleration processes.

SEPs play important role in the present day society. Our modern life is strongly dependent upon information from satellites, weather forecast,car navigation, TV and so on even though we are not aware of them. SEPs hitting electronics of these satellites produce errors in their function or can damage them. Energetic particles are also dangerous for human health when they hit the human body. Usually we are protected by thick absorber of the earth's atmosphere, but astronauts and airplane crew are directly irradiated by particles. Protection of the satellite electronics and human body from these radiations is important and it is one of the important topics in space weather forecasting. To understand the basic processes of particle acceleration and transport is important to predict the arrival of SEPs.

In SEPs, both charged and neutral particles carry the information of the acceleration site. They arrive at Earth via different paths through different processes. That means for compiling the observational data to the acceleration information, we need to understand these processes as illustrated in Figure-1. In the other words, the aim of studying SEPs is to understand these processes in a consistent manner. Because any observation method has advantages and disadvantages, approaches from various channels are inevitable. In this lecture, I first introduce various observations of SEPs together with technique. Then I introduce what happens to the particles from when they are accelerated until they are observed. These are acceleration, transport and interaction processes.

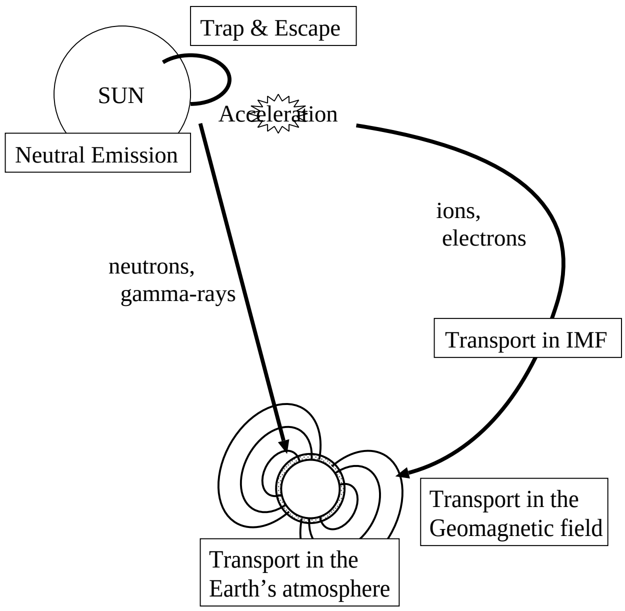

Fig. 1. A schematic view of the processes taking place on the SEPs.

2 Observations of SEPs

Because SEPs are absorbed in the earth's atmosphere ($\sim$1000 g/cm^{-2}or 10 m water equivalent at the sea level), observations are made both in space and on the ground depending on particle species and energy. Electrons and gamma-rays can be only observed in space. For ions with their energies below 100 MeV, they can only be observed from space because the atmosphere strongly attenuates the particle flux [?]. Only ions above 100 MeV can be observed by ground based detectors. In this section, I introduce a subset of various observations, those are ground-based observations of ions (presumably protons) and neutrons, and space observations of gamma-rays.

2.1 Proton observations

Events where particles are observed by ground-based detectors are called Ground Level Enhancements (GLEs). GLE events are usually identified with a world-wide network of Neutron Monitors (NMs). NMs are distributed over more than 50 observatories throughout the World to monitor the long-term intensity variation of galactic cosmic-rays. Because the particles entering the atmosphere experience inelastic collisions several times, surviving particles at ground level are mainly neutrons. NMs detect them with a high efficiency [?] [?]. As discussed in Section-3.2, protons travel along the interplanetary magnetic field (IMF) and some fraction is diffusive. This means, in the early phase of a GLE, particles arrive at the the earth from the direction of IMF connected to the Sun while it becomes more isotropic in the later phase. The detailed conditions are different from event to event. Also due to the geomagnetic field, each NM at different observational sites has different sensitivities to the direction and rigidity. This means that the network of the NMs acts as a single powerful detector that is sensitive to the direction distribution (anisotropy) and energy spectrum of primary protons in the interplanetary space. Bieber et al. organize such a network into *"the Spaceship Earth"* and measures the properties of protons [?]. Energy spectrum sometimes continues up to 10 GeV, but at the same time there are indication of roll-off in the highest energy that means the acceleration is limited at that energy. An energy spectrum derived by Bombardieri et al. [?] in case of the 15 April 2001 GLE is shown in Figure-2.

Observations of GLEs with non-NM type detectors are also carried out. For example, Solar Neutron Telescopes (SNTs) based on the plastic scintillators [?], Milagro which uses a large water pool designed for gamma-ray astronomy [?], and the URAGAN muon hodoscope [?]. These new experiments have several detection channels with different sensitivity in energy and direction so that observations at a single station also give some information in energy spectrum and anisotropy. Continuous monitoring in the low energy range by the *GOES* satellite is also important to cover a wide range of energies.

2.2 Neutron observations

Because of its electrical neutrality, neutrons are not affected by magnetic fields. That frees us from the problem of transport in the interplanetary magnetic field and geomagnetic field. On the other hand, because any acceleration process works only on charged particles, neutrons are emitted as secondary particles through some interactions as introduced in Section-3.3. A dozen solar neutron events are so far recorded mainly by NMs. To detect relatively low flux secondary neutrons effectively, a dedicated network of the SNTs is also in operation [?]. The

SNTs are installed on high mountain tops at low latitudes to avoid large attenuation in the earth's atmosphere.

Because the neutrons fly directly from the emission site to the Earth, we can derive emission time profile if we can measure the velocity of neutrons that is a function of energy. The SNTs are designed to measure the energy of particles and then determine the emission profile. Sako et al. reported a long-lived emission of neutrons for the event occurred on 7 September 2005 from the observations of SNTs [**?**]. Energy spectra of solar neutrons are well explained by power law up to GeV energy [**?**] though in the case of 7 Sep a cutoff at 500 MeV is indicated [**?**].

To avoid atmospheric attenuation, space observations are ideal though they can not cover wide effective area and high energy measurement. Actually, the first detection of solar neutron was made by an instrument on board the *Solar Maximum Mission/Gamma-Ray Spectrometer* [**?**]. So far observations of solar neutrons in space are made by gamma-ray detectors. A dedicated detector of solar neutrons proposed by Imaida et al. will be launched in 2009 [**?**]

2.3 Gamma-ray observations

All observations of solar gamma-rays are made in space. As discussed in Section-3.3, gamma-rays are emitted through some different processes so that they require different observation techniques. Below 20 MeV, an important aim is to measure the gamma-ray emission lines

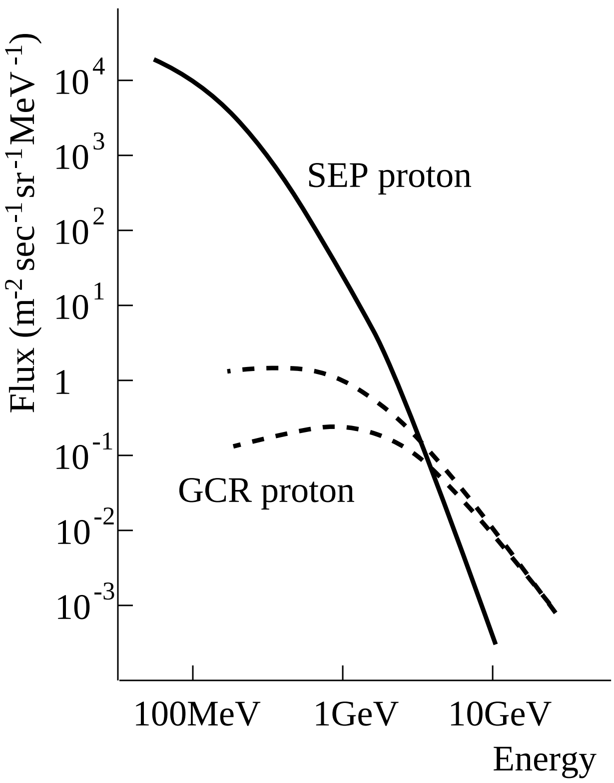

Fig. 2. Energy spectrum of the SEP observed in the 15 April 2001 GLE (solid line) together with the Galactic Cosmic-Ray proton spectra (dashed lines). SEP particles sometimes overwhelm the stable GCR flux below 10 GeV. Two dashed lines indicate the GCR fluxes modulated by the different solar activity [**?**].

from excited nuclei or electron-positron annihilation. In this energy range, excellent energy resolution of semi-conductor detectors is required. Observations by the *Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI)* are now in operation [**?**]. The *RHESSI* satellite also succeeded the first imaging of the gamma-ray emission site in this energy range. Hurford et al. reported the ions and electrons lost energy on the solar surface at slightly different places [**?**].

At higher energies, gamma-rays are emitted via decay of π^0 mesons. In that energy range, wide dynamic range and large effective area is more important than resolution. *SMM/GRS*, *CORONAS-F/SONG* are dedicated for such observations. Detectors not dedicated for solar observations such as *Compton Gamma-Ray Observatory/Energetic Gamma-Ray Telescope Experiment* also have a chance to make important observations [**?**].

These ion induced gamma-rays are overlaid with a continuum of the electron induced bremsstrahlung radiation as shown in Figure-3 [**?**].

As is the case of neutrons, gamma-rays also directly arrive from the emission site. Of course, as they travel with the speed of light, no energy dependent time dispersion occurs like the case of neutrons. Time profile of gamma-rays is a good estimator to know when ions interact with solar atmosphere [**?**]. On the other hand, because the effective energy of the parent ions to excite nuclei is below 100 MeV, we are not sure if the indicator is valid for the relativistic ($\sim$1 GeV) ions.

3 Acceleration, Emission and Transportation of SEPs

3.1 Acceleration of SEPs

Acceleration mechanisms taking place near the sun are not well determined. Simply the models are classified as 1st order Fermi acceleration (or shock acceleration), 2nd order Fermi acceleration (stochastic acceleration), and DC electric field acceleration. The idea of shock acceleration is widely used to explain the accelerations in various astrophysical objects such as supernova remnants. A theoretical formula, proposed by Ellison & Ramaty, models a power law form spectrum with an exponential cut-off [**?**]. A formulation for the stochastic acceleration was made by Ramaty & Murphy [**?**]. Bombardieri et al. have compared an observed GLE spectrum with those predicted by two models and concluded that both mechanisms worked at different stages of a single event [**?**]. However we have not reached at a general conclusion to explain all SEP events.

3.2 Transport of SEPs

As moving charged particles feel Lorentz force in the magnetic field, they can not directly travel to the earth. Gyro-radius of a 100 MeV proton in the magnetic field of 3×10^{-5} Gauss, that is typical near the earth's orbit, is 5×10^{8} m. Because this is far smaller than 1 astronomical unit, SEPs travel along the field line called the Parker spiral. The field line crossing at the Earth originates from the western limb of the sun so that the charged particles emitted in this area arrive at the earth more efficiently and more rapidly. Particles emitted along the direction of the field line (pitch angle $\sim$ 1) can arrive at L/v after emission (here, L is the length of the magnetic field and v is the velocity of the particle). By measuring the first arrival particles, the emission time can be estimated [**?**]. At later times, the arrival of particles with various pitch angle makes such analysis impossible. Though the prompt component comes along the direction of the field line, the later component is more isotropic. Also changes in the pitch angle (pitch angle scattering) makes the transport diffusive and the distribution more isotropic. Transport in the IMF together with the geomagnetic field effect is well studied and applied in the analysis of GLE by Saiz [?] and Bombardieri et al. [?], for example.

3.3 Emission of neutral particles

Neutral particles are emitted through interaction between charged particles and solar atmosphere. Particles moving down from the acceleration site to the solar surface efficiently contribute to these emissions. Solar surface connected to the acceleration site is thought to have loop structure of magnetic field. In general, the loop has stronger field on its feet so that particles with small pitch angle are reflected (mirrored) and trapped in the loop. Particles penetrating deeper in the atmosphere or trapped in the loop longer time have more chance to interact with the atmospheric elements. High energy neutrons are directly produced by a single inelastic interaction. High energy π^0 mesons are also produced by a single inelastic interaction and immediately decay into high energy gamma-rays. Low energy neutrons produced

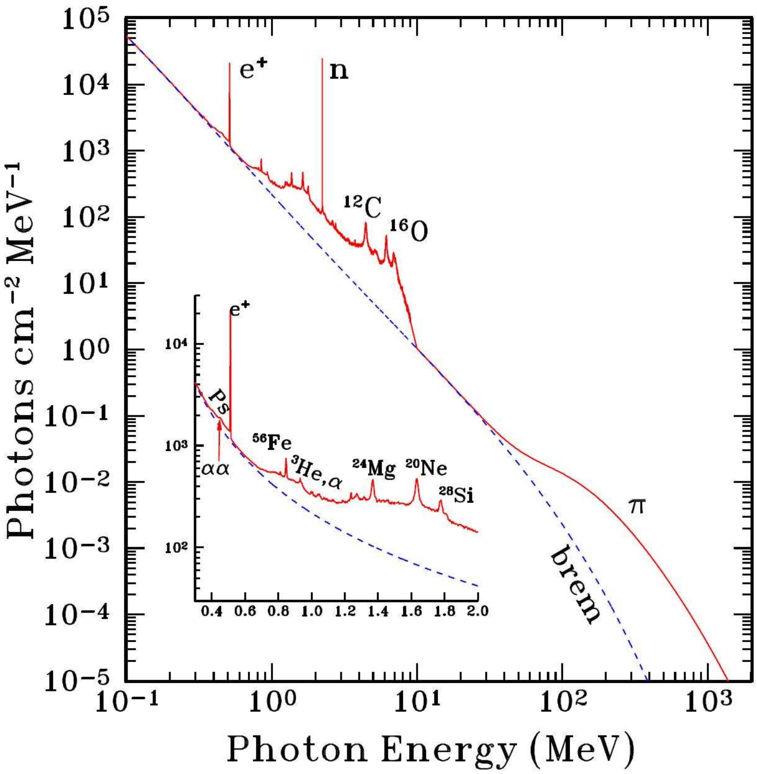

Fig. 3. Theoretical solar flare gamma-ray spectrum. Characteristic feature made by line emissions is seen below 20 MeV overlaid with continuous bremsstrahlung emission. Continuum above 100 MeV made by π^0 meson decay shows a distinctive feature from bremsstrahlung.

in scattering are thermalized with a time scale of 100 sec. Thermal neutrons are captured by hydrogen nuclei and produce excited deuterium. Finally the deuterium emits 2.223 MeV line gamma-ray 100 sec delayed from the other emission. Nuclei like carbon and nitrogen are also excited directly by charged particles and emit line gamma-rays without delay. These complicated processes are modeled and applied to the observed neutron and gamma-ray profiles [**?**] [**?**].

Through these processes it is clear that the spectra of the neutrons and π^0 decay gamma-rays reflect the spectrum of the parent ions. Although the intensity of the line gamma-rays carries only the integrated information of the parent spectrum, comparison of the intensities in different lines can give a good estimate of the parent spectrum [**?**].

4 Summary

Though I could not cover the topics on electrons, ions except proton, they are also important aspects in the study of SEPs. In the observations of ions, not only atomic number but their charge state also gives us important information. The study of SEPs presents a challenge to understand these variety of observations and trace them back to their origin, particle acceleration. Probably, the nature of the particle acceleration on the sun has some variations. Systematic studies to classify them are important. The study of heliospheric phenomenon seems sometimes quite complicated compared with the other astrophysical studies. This is due to our observations are far rich and far precise. SEP study should contribute to the general astrophysics as only it is based on the in-situ observations.

Finally, I want to discuss shortly about the highest energy particles. Figure-4 is the famous Hillas diagram showing possible highest energies for various celestial objects [**?**]. The idea is when the gyro-radius of a particle reaches at the object size, no more acceleration is expected because such a particle escapes from the object. Typical size versus magnetic field of various objects is plotted together with the corresponding maximum energy. Though the plot is originally introduced to estimate the possible sources of the highest energy cosmic-rays at 10^{20} eV, it also predicts the highest energy of SEPs. With some possible conditions, heliospheric phenomenon are capable to accelerate particles up to TeV energy. So far, we know the energy of SEPs reaches 10 GeV. To uncover this 2 orders of magnitude difference is one of the interesting challenges in SEP studies and also for general particle acceleration studies.

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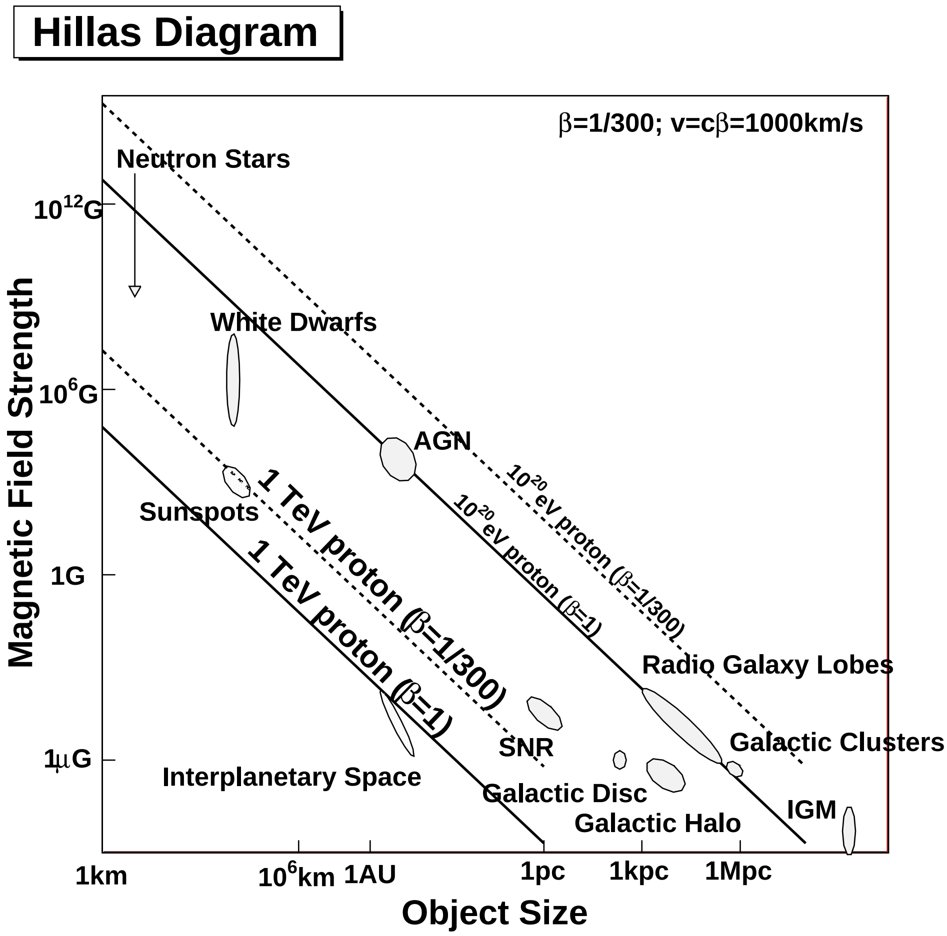

Fig. 4. The Hillas diagram showing the typical magnetic field strengths and sizes of various celestial objects. The maximum achievable energies (1 TeV and 10^{20} eV) are also drawn in the figure.